2
The new frontier fibers?

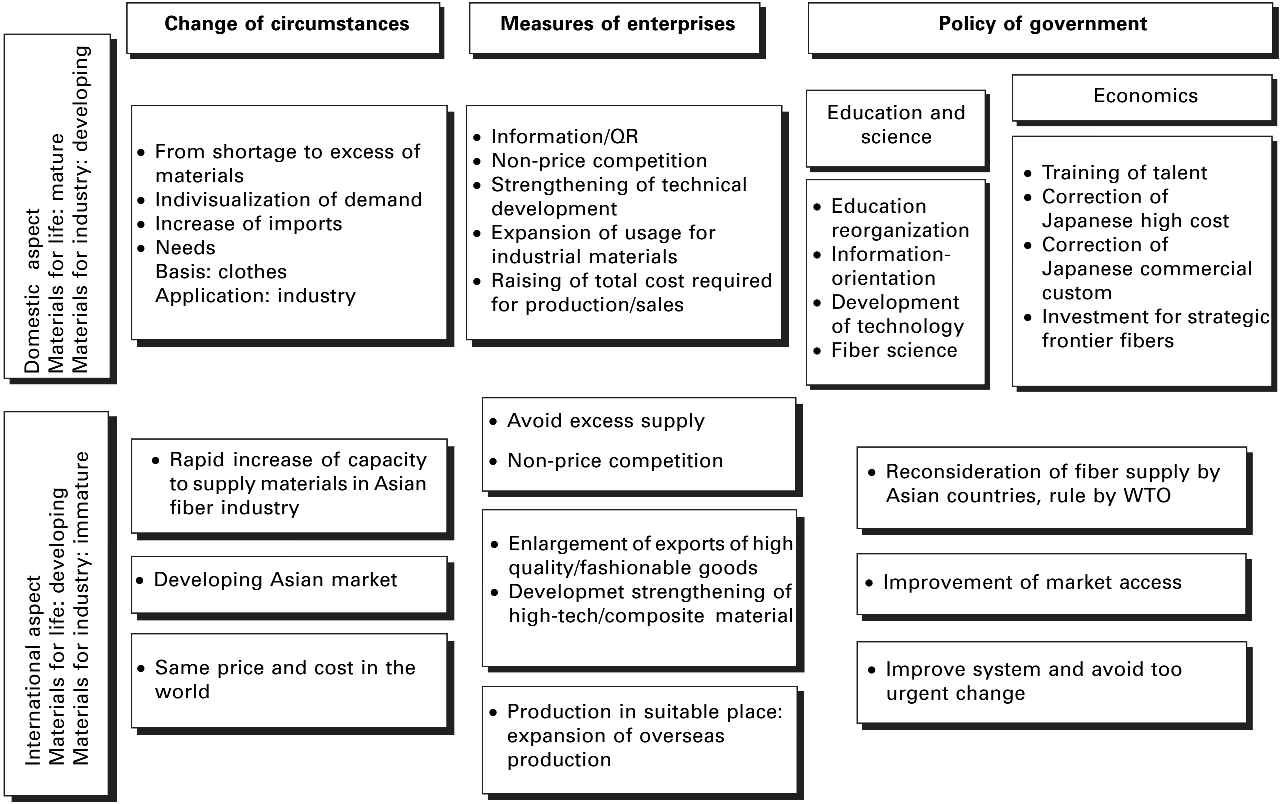
2.1 Enlargement of the frontier in a fiber competition age

General-purpose and high-tech fibers have been well developed in Japan. In Asia, these fibers and high-tech fibers are still under development. Food, clothing, housing, and energy are the national priorities in the United States. The status of fibers in this competitive age is shown in Fig. 2.1. Their application to industry is growing apace, fueled mainly by the high-tech fibers.

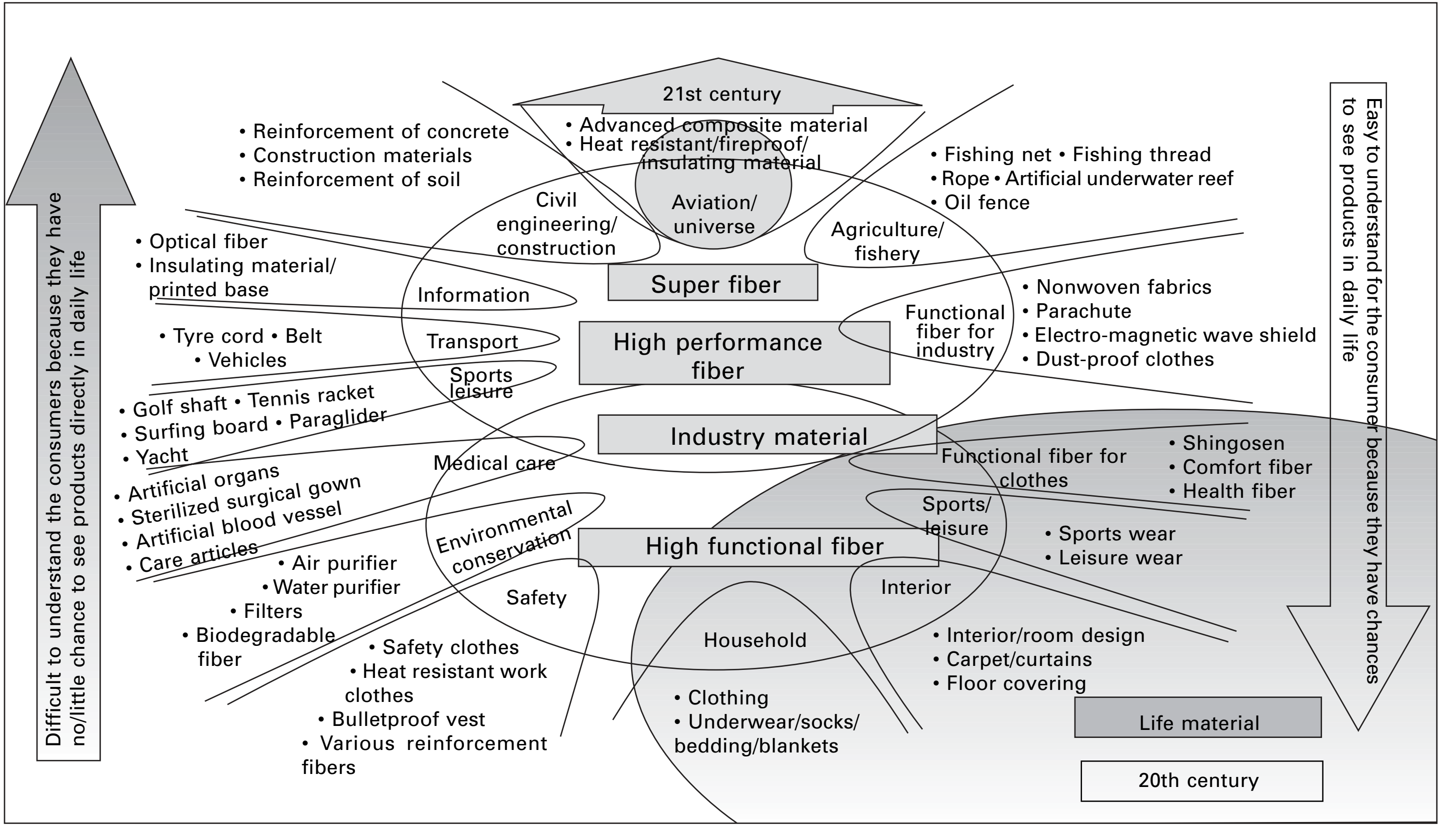
The high-tech fibers can be regarded as high function fiber, high aesthetic fiber having characteristic feel, and high performance fiber with specific properties to make them useful as industrial materials. Superfiber is one such high-tech fiber and is expected to grow in importance and application. The development of fiber usage in the twenty-first century is shown in Fig. 2.2.

2.1.1 Fiber as a major technical strategy in Japan

In June 1999, the Japanese government decided on 'the policy to stimulate employment and to strengthen industrial competition'. Fiber was selected as one of the main technical strategies, together with other technologies such as biotechnology, information technology, medical care, welfare, and the environment. The emphasis is not merely on fiber for textiles, and involves a fundamental review of the field. Fiber was announced as one of the national industrial technical strategies in March 2000 in Japan, twenty years later than in the United States. The key areas involved in this overall thrust are 'ageing society', 'health and medical care', 'stable supply of energy', 'global environmental', 'conservation', 'economical development', 'information technology (IT)', 'Kansei (aesthetic) information', and 'circulative economic society'. High-tech fiber can play an important role in all of them. In an ageing society, for example, high function fiber can contribute in the field of health and medical care, or as an optical fiber and a new material in the



2.1 Status of fibers in competitive age (Source: H. Ishige, Special Relay Symposium Proceedings, p. 23, The Society of Fiber Science and Technology, Japan, April, 1996).



2.2 Development of fiber usage in the twenty-first century.

information technology revolution. Aramid fiber can decrease size and weight of a mobile phone, fiber can shield electromagnetic waves. Biofiber produced by microorganisms, biodegradable fiber, nanofiber and miracle fiber can exercise the pull needed by industry in the twenty-first century.

Enlargement of usage for industry materials

The enlargement and development of high-tech fiber as an industrial material depends on an understanding and the solving of market demand. Technology can be used to solve the demand and in the process requires new materials. The performance required for various application fields is shown in Table 2.1. New industry materials have many application fields in the market. The key words to launch fiber into the twenty-first century are: high performance, high function, high composite, and soft. Superfibers developed by many companies are good examples of pursuing these ultimate properties. The silk-like ultra-fine fibers are the result of pursuing biomimetics, copying the operating system of the silkworm. The strength of nylon and polyester fiber is only 3% of their theoretically ultimate value, but an increase of the strength to 5–6% of the theoretical value is required. It is seemingly a small improvement, but it calls for dedicated research over the next ten years. Cooperation among industry, academia and government will contribute to solving this problem and creating a new industry. Moreover, it will contribute to the fiber industry not only in Japan, but also in other parts of the world. These needs and development of the usage of superfiber are shown in Table 2.2.

2.2 'Selection', 'concentration' and 'originality' development on a world-wide scale

International competition in fibers became intense at the turn of the millennium. In the twentieth century, polyester filament was the most popular, but now selection, focusing and reorganization have already started.

2.2.1 Asian fiber manufacturers hotly pursue Europe/US manufacturers

In March 2000, the Japan Chemical Fibers Association reported their research on reorganization of synthetic fiber companies in Europe and USA. According to the report, three out of every five of the main manufacturers of synthetic fibers in the world changed their emphasis to other business in the past decade. The chemical giants of Europe and the United States moved their main product lines from synthetic fibers to life science and specialty chemicals, because of their stability and high profit margins. Accompanying this, and in

Table 2.1 Performance required for various application fields

	High strength	High modulus	High toughness	High tear strength	Shock resistance	Abrasion resistance	Fatigue resistance	Durability	Dimension stability	Dye stability	Lightweight	Transparency	Air permeability	Heat retention	Heat resistance	Insulation	Fire-proofing	Fire prevention	Fire resistance	Antiweatherability	Moisture absorption	Moisture permeability	Water absorption	Water-proofing	Water repellency	Electric controlling	Electric insulation	Bacteria-proofing	Fungi-proofing	Chemical-resistance	High adhesive property	Ease of storage	Safety
Clothes	○							○	○		○		○	○		○	○				○	○	○	○	○	○							○
Bedding	○							○			○		○								○							○	○			○	
Interiors								○						○				○			○		○			○		○	○				○
Life materials	○									○	△	△	○					○				○		○					△		△		
Agriculture/ marine products	○	○	○									△			○					○													
Industry	○		○					○																			△			△			
Traffic/transportation	○		○	○	○	○	○		○		○																						
Civil engineering construction	○	○	○	○	○	○	○										○ ○			○ ○				○ ○						○ ○	○ ○		
Ocean development	○		○		○			○			○																						
Aviation/space	○		○		○			○			○				○	○	○																○
Energy development														○	○		○														○		○
Medical care											○																						
Information	○	△						○	○		△																						
Fire fighting	○		○			○					○				○	○		○	○	○													
Defense/munitions	○		○		○	○	○	○			○		○		○		○	○			△	△		○	○	△	△					○	

From K. Matsumoto, *Polymer Digest,* **36**(6), 4 (1984)
○ = Very important property.
△ = Less important property.

Table 2.2 Needs and development of the usage of superfiber

Needs	Lightening and high function are necessary for protection of global environment, resources saving, and energy saving Enlargement of industry frontier
Application development	Pursuit of limit performance (strength, high modulus) High performance with specific function (plus alpha function) (Surface property, shrinkage property, durability) New molding and processing technology, development of new matrix Development of evaluation technology Decrease of cost (balance between cost and performance) More severe after collapse of bubble economy Development plans for disposal and recycling
Expansion of application	Not only required functions but also plus-alpha functions are important. Acceptable price to consumers

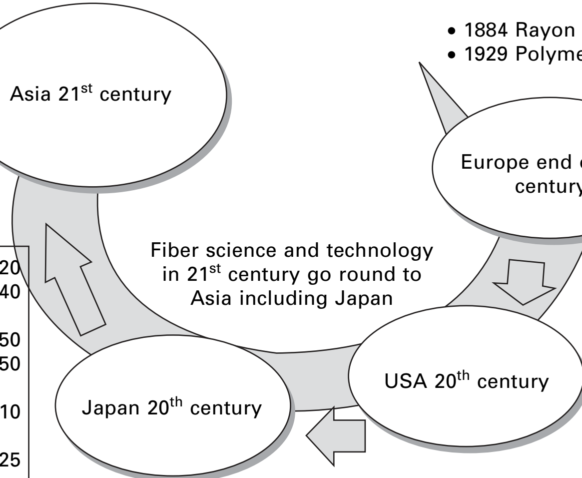
hot pursuit, Asian fiber manufacturers have developed to occupy 60% of the world production of synthetic fiber. Of course, for special fields the Western manufacturers continue to maintain their share of production in speciality fields, for example acrylic fiber (Bayer, German), polyester and acrylic fiber (Monte Fiber, Italy), polyester and nylon (Allied Signal, USA), and polyester and nylon (Welman, USA). Four companies in Europe, ICI in the UK, Hoechst in Germany, Rhone Poulenc in France, and Akzo in Netherlands are included in the top ten manufacturers of polyester production in the world in 1998. However, in 2003 Asian capital companies, such as Nan Ya in Taiwan/USA, Tuntex/Xiang Lu in Taiwan/Thailand/China, and Reliance in India, occupied the top spots. The market share by Asian companies will continue to increase due to the rise of Chinese companies, such as Shanoxing Yuandong and Yizheng as shown in Fig. 2.3.

Rayon was invented by Chardonnet (France) in the latter half of the nineteenth century, nylon by Carothers (USA) in 1932, polyester by Whinfield and Dickson (UK) in 1940, and Shingosen in 1988 by the Japanese, but the report indicates that the new streams of fiber in the twenty-first century will flow from Europe, USA, to Asia, including Japan. The new wave which will bloom in the twenty-first century is shown in Fig. 2.3. Fiber science is still studied actively in Europe and the USA and completely new fibers can be developed in the twenty-first century.

2.2.2 Studies in Japan now watched by the world

In Japan, fiber science is still being studied, not only at universities with Faculties of Fiber Science, but also at universities without these faculties. For example, plastic optical fiber (POF) from acrylic fiber and fluorine containing fibers are investigated by Professor Y. Koike (Keio University), Predicted rank of polyester production capacity of each manufacturer in 2010 (1000t/year)*

Shaoxing	China	1,620
Yizheng	China (Part of Sinopec)	1,540
Reliance	India	1,350
Nan Ya	Taiwan, USA, Vietnam, China	1,250
Far Eastern Textile	Taiwan, China	1,110
Tuntex/ Xiang Lu	Taiwan Thailand, China	1,025
Zhejiang Rongsheng	China	930
IndoRama • Ass.	Indonesia, Thailand, India	896
Huvis	Korea, Indonesia,	873
Sabfabgxiang Group	China China	860



- 1884 Rayon (France) Chardonnet
- 1929 Polymer theory (Germany) Staudinger
- 1932 Nylon 66 (USA) W.H. Carothers
- 1938 Nylon 6 (Germany) P. Schlack
- 1939 Vinylon (Japan) I. Sakurada
- 1940 Polyester (UK) J.R. Whinfield and J.T. Dickson
- 1942 Acrylic fiber (USA) Du Pont
- 1946 Acrylic fiber (USA) CCC
- 1949 Acrylic fiber (USA) Chemstland
- 1951 Acrylic fiber (USA) AC
- 1951 Acrylic fiber (Germany) Cassella
- 1955 Polypropylene (Italy) G. Natta

- 1986 K-II (Kuraray)
- 1988 Shingosen (each company)

- 1999 Solo (Asahi (Chemical)
- PDO + TPA (Shell Chemical)

- 1937 Elastic fiber (Germany) O. Bayer, H. Rink
- 1959 Heat-resistant fiber (USA) Aramid Du Pont
- 1961 High modulus fiber (Japan) PAN-based carbon fiber
- 1979 PE gel spinning (Netherlands) Stamicarbon
- 1975 Arylate (USA) Du Pont, liquid crystal
- 1977 Arylate (USA) Celanese, liquid crystal
- 1980s PBO (USA) US Airforce→SRI→Toyobo

Polylactic acid
Biodegradable fiber
- 1998 TERRAMAC (Unitika)
- 2000 LACTRON

* From *Chemical Fiber International*, 53, 395 (2003)

2.3 New wave expected to bloom in the twenty-first century.

synthesis of ultra-thin fibers having nano-structure are now investigated by Professor T. Aida (University of Tokyo), and strong fiber both in lateral and vertical directions is being developed by Professor C. Kajiyama (Kyushu University). Glass-based optical fiber is suitable for key communication networks requiring large capacity and high speed. However, POF is suitable for the connection of main lines in each home because it is cheap and easy to connect. In the twenty-first century, POF could be used in circuitry in the home instead of copper wire. Professor Aida has synthesized ultra-thin and strong fiber, which corresponds in properties to the spider's thread. Professor Kajiyama has made fiber strong in a lateral direction to produce new optical fiber and fiber with progressively increasing function.

2.2.3 Major US companies advance in fiber industry

Two major US companies have advanced in the fiber market. One is Shell Chemicals, part of the international petroleum company, and another is a joint enterprise of Cargill and Dow Chemicals, 'Cargill Dow Polymers' (CDP). Shell Chemicals has started production of the 3GT polyester, PTT. Although PTT fiber had already been produced by Asahi Kasei under the trade name of SOLO, Shell Chemicals gave a fashion show in Paris in March 2000 appealing to the world fiber manufacturers. CDP produce polylactic acid (PLA) from carbohydrate in corn and is a biodegradable polymer. Kanebo and Unitika import PLA from CDP and produce 'Lactron' and 'Terramac', respectively.

2.2.4 Development of biodegradable fiber

In the last century, synthesized polymer material products made from fossil resources resulted in mass production and mass consumption, which caused the two serious problems of exhaustion of resources and waste material. The problem of waste material takes place since the synthetic fibers drop out of material circulation (carbon circulation) since they are not biodegradable. The problem of resource exhaustion is caused by the consumption of raw materials, for synthetic fibers are dependent on fossil resources such as petroleum. It is expected that the extent of petroleum resources will tend to decrease after the peak of mass production at the beginning of this century, and it is said that it could be exhausted in the medium term. It is a problem for synthetic fibers whose raw material depends on the fossil resources.

In the relationship between humans and plants, natural fibers, such as silk, cotton, and wool, have their own excellent properties. The synthetic fibers do not have these excellent properties. Nylon, polyester and polyacrylonitrile have appeared as a substitutes for silk, cotton, and wool, respectively, since they are tougher than the natural fibers. However, they do not have functions as excellent as those of the natural fibers. So natural and synthetic fibers have to be used in the fields where they can show their best properties. In addition to functions and performance, the environment should be also considered when one develops materials and technologies. The most important thing that one should consider is a 'sustainable society'. In developments of ecological products and technologies in the synthetic fiber industry, there are, of course, 'problem areas' and 'defensive measures'.

'Problem areas' are UV-cut fibers for the prevention of the depletion of the ozone layer, several filters for water and air cleaning, oil barriers for prevention of sea pollution, water-swelling fibers for prevention of tropical forest decrease and desertification, etc.

'Defensive measures' are recycled fibers, counter penetration membranes for global warming prevention, biodegradable fibers for waste material decrease, environment beautification, etc. Much thought and effort will be required to introduce them into society.

Natural recycle system of biodegradable polymers

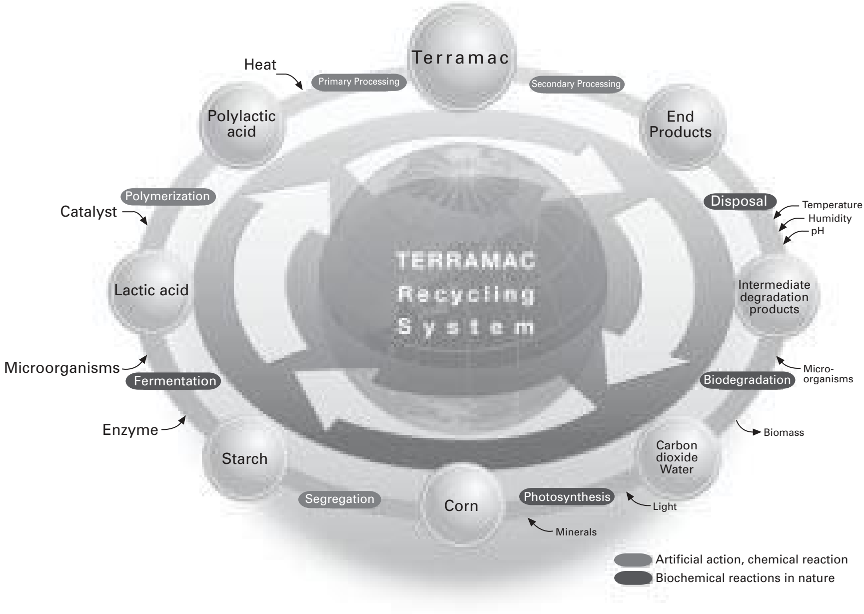
Biodegradable polymers are expected to be adaptable to carbon recycling systems like the natural organic materials in the last century. Recyclable carbohydrates obtained from plant resources such as corn as a raw material are degraded by enzymes to glucose, which can be fermented by bacteria into lactic acid. The resulting lactic acid can be polymerized to poly(lactic acid). This polymer can be shaped into fibers – films which are biodegradable materials. Hydrolysis takes place in the polymer in compost or at the beginning of the degradation process in the natural environment. In the second half of the process, hydrolysis by enzymes secreted by microbes changes the polymer into water-soluble oligo-lactic acid or lactic acid monomer, which enters the microbe cell to change finally into carbon dioxide and water. The carbon dioxide can be used to synthesize carbohydrates in plants. Figure 2.4 shows the natural recycle system of the biodegradable polymer, Terramac® by Unitika.

Development of biodegradable fiber, Lactron™

Table 2.3 lists companies who manufacture and develop goods using polylactic acid. Lactron™ is a poly(lactic acid) fiber produced by Kanebo Gohsen and was given the Technology Award of The Society of Fiber Science and Technology, Japan in 1999.

Processes for the development of Lactron™

Kanebo Gohsen began technological studies for the production of biodegradable polymer fiber. They found that poly(lactic acid) is the most



2.4 Natural recycling system of biodegradable polymer (Unitika).

Table 2.3 Manufacturers and developments of goods using polylactic acid

Manufacturer	Trade name
Polylactic acid products	
Kanebo Gohsen	Lactron*
Unitika	Terramac
Mitsubishi Plastics	Ecoloju
Kuraray	Plastarch
Toray	Ingeo
Polylactic acid	
Cargill Dow (USA)	Nature Works
Mitsui Chemicals	Lacea

* Production finished in 2004.

suitable material for manufacture with regard to transparency, strength, and costs.

In January 2000, Kanebo Synthetic Fibers announced an association with Cargill Dow Polymers (USA). Now they are developing markets associated with the building and operation of production plants for poly(lactic acid). They selected poly(lactic acid) because:

1. it is a non-petroleum-derived recyclable resource (the raw materials are plants such as corn and sugar beets)

2. it has correspondence with environmental problems (biodegradable means compostable, low combustion heat, no harmful gas), and
3. it has excellent properties and processability for materials (fibers) with melting point, strength, crystallinity suitable for practical use.

Characteristics of Lactron™

Lactron is manufactured by melt spinning like nylon and polyesters. To obtain high performance fiber, a high technology of spinning as well as quality and strict specification of raw plastics are required. Its characteristic properties are summarized in Table 2.4, along with those of polyester and nylon.

The characteristics of Lactron™ include:

- fiber strength is as great as that of nylon and polyester, sufficient to produce fiber material.
- Young's modulus is between that of polyester and nylon, just a little more than nylon.
- soft touch
- good water diffusion, sweat-absorbable and rapid-dry
- interim-twisted processable
- low refractive index, mild gloss
- stainable by dispersed dye at 98°C, ambient pressure
- melting point is 175°C, higher than other biodegradable polymers.
- chemical structure is polyester, so absorbance is low.
- anti-bacterial, weak acid, retains humidity.

Table 2.4 Characteristics of Lactron fiber (Kanebo)

	Lactron	Polyester	Nylon
Physical properties			
Density	1.27	1.38	1.14
Melting point (°C)	175	260	215
Glass transition temperature (°C)	57	70	40
Absorption (%)	0.5	0.4	4.5
Combustion heat (cal/g)	4500	5500	7400
Fiber character			
Strength (cN/dtex)	4.5–5.5	4.5–5.5	4.5–6.0
Stretch (%)	30	30	40
Young's modulus (kg/mm^2)	400–600	12000	300
Stain			
Dye	dispersed	dispersed	acid
Staining temperature (°C)	98	130	98

Thus Lactron™ has fiber properties and processability comparable to those of conventional polyester and nylon.

Biodegradability of Lactron™

Biodegradability of Lactron™ is estimated by various practical methods, assuming the various locations where the products are used.

The strength of Lactron™ decreases within a few years in soil. Decrease in weight follows a decrease in strength. In particular microbes and bacteria in active sludge decrease the strength immediately. The strength becomes almost zero within one year. According to results obtained by the standard compost method (ISO 148550), Lactron™ is completely degraded in about 70 days.

Development of goods using Lactron™

Lactron™ is processed in various shapes such as filament, staple, monofilament, spanbond, flat yarn spinning fiber, textile, knitting, non-weaved cloth and made into industrial materials and general wearing materials. Table 2.5 shows examples of the development of uses for Lactron™.

In keeping, with concept of biodegradation, Kanebo Gohsen released a mixture of Lactron™ and natural fibers such as cotton or wool in January 1998, and developed the goods widely. The main merit of 'corn fiber' is that it can solve the problem of dumping while keeping the advantages of conventional mixtures of synthetic and natural fibers.

2.3 New fibers for the next generation have arrived

The new fiber material 3GT polyester fiber (PTT fiber) has attracted attention in Japan, Europe and the United States since the spring of 1998. The raw

Table 2.5 Examples of development of uses for Lactron (Kanebo)

Classification	Use
Non-clothes	
Civil engineering and construction	Plant nets, non-weaved cloth, mat, plant soil, reinforcing material for weak soil
Agriculture	Easy covering material, anti-weed net, bags, net for
Fishery	vines, bind tape, fishing nets, fishing line
Life	Packaging, sanitation, convenience goods, leisure goods, suture thread, absorbance material
Clothes	Inner wear, outer wear, wearing goods

materials for 3GT fiber are somewhat different from those for polyester or PET fiber and are shown in Table 2.6. PET fiber is made of ethylene glycol and terephthalic acid and called 2GT. 3GT is called PTT fiber and made of 1,3-propane-diol (PDO) and terephthalic acid. Ethylene glycol in 2GT is exchanged for PDO in 3GT. 3GT itself is a well-known material and is not at all new. However, the yield of PDO in synthesis was low, so that the cost of production of PDO was high and could not compete with ethylene glycol. However, now a method to produce PDO cheaply has been developed by Shell Chemicals and Du Pont.

2.3.1 Petrochemical companies advance in fiber industry

Cos, an affiliated company of Texaco, produced the PTT fiber Cortera® in Italy and Spain, and launched the fiber at a fashion show in Moulin Rouge, Paris, which attracted attention from all over the world. PTT fiber is also produced by Asahi Kasei, Japan, and other manufacturers in Korea and Taiwan. Asahi Kasei decided to produce Solo® in 1998 using PTT provided by Shell, and started production in the latter half of 1999 at 1000 tons per year. Production will increase to 5000 tons per year. Asahi Kasei has applied for patents concerning Solo® production. Based on 127 patents, they will advance an intellectual property right strategy. Most of the patents are concerned with dyeing and production of fabrics. When the users of Solo develop new products, they can use these patents and decrease the time required for production.

Table 2.6 Raw materials for 2–4 GT fibers

Name of fiber	Abbreviation	Raw materials	Note
Polyethylene terephthalate fiber	2GT (PET)	Ethylene glycol and terephthalic acid	Polyester fiber Produced in many countries
Polytrimethylene terephthalate fiber	3GT (PTT)	1,3-propane-diol and terephthalic acid	Shell Chemicals 'Cortera®' → Asahi Kasei 'Solo' Du Pont: Biotechnology to produce raw materials
Polybutylene terephthalate fiber	4GT (PBT)	Butane-diol and terephthalic acid	Used as ester component in highly elastic fiber 'REXE'

2.3.2 Development of PTT fiber 'Solo'

Asahi Kasei succeeded in synthesizing a new fiber composed of poly(trimethylene terephthalate). Solo™ was released in 1999. PTT (3G) is prepared by condensation of terephthalic acid or dimethyl terephthalate and 1,3-propane diol (PDO). PTT is a polyester homologous to PET, but it has different properties from that of PET. There were many difficulties to overcome in the manufacture and processing of Solo, these but were overcome and the technology has now been established. PTT is different in the crystal and amorphous structure, so the fiber properties of Solo are: new soft touch, reversible stretch, stainability at low temperature, form stability, and light and adhesive proof.

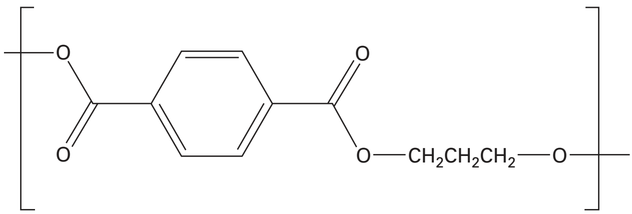
Asahi Kasei will develop Solo further for textiles and materials applications where Solo's characteristics are best displayed, as well as for raw fiber, processed fiber, combined fibers with natural fibers or cellulose fiber. The growth of Solo is so spectacular that it has been classified as one of four master fibers in use today in the goods field, exceed spandex in cost and performance.

Polymer structure and fiber performance of PTT

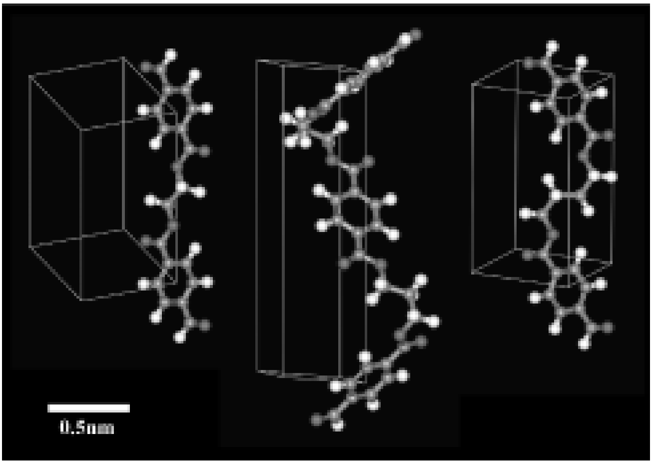
Figure 2.5 shows the chemical structure of PTT. PTT has a crystal structure as shown in Fig. 2.6.

Crystal elasticity and elongation energy of the crystals of PTT are much smaller than those of PET. As shown in Fig. 2.6, PTT molecules bend in a Z shape. This is the part of the molecule that can be bent with a small amount of stress, resulting in low elasticity (or new soft touch) and reversible stretch. The Z-shaped structure of PTT produces mechanical properties such as large limit of elasticity and high recovery of stretch. The reversible stretch is significant in the processed fibers.

These properties have not appeared in conventional fibers. Most applications of PTT are in the areas of cloths and industrial materials. Stretch cloth is a new trend, so Solo is expected to be used widely here. In industrial materials, developments are making use of Solo's elastic properties. The characteristics of Solo are summarized in Table 2.7.



2.5 Chemical structure of PTT (Asahi Kasei).



PET PTT PBT

2.6 Crystal structure of PET, PTT and PBT (Asahi Kasei).

Table 2.7 Characteristics of Solo (Asahi Kasei)

Characteristics	Unit	Solo	PET	PBT	Nylon 6
Draw strength	cN/dtex	3.5~4.0	3.7~4.4	3.5~4.0	3.5~5.3
Stretch	%	42~48	30~38	30~40	30~50
Elasticity	cN/dtex	22	90	22	20–30
Recovery from 20% stretch	%	85	29	40	62
Density	g cm^{-3}	1.34	1.38	1.35	1.14
Contraction in boiling water	%	12~13	7	7	17
Melting point	°C	230	260	230	220
Weather proof		good	good	good	strength degradation sometimes color changes to yellow
Color stability		good	good	good	sometimes not enough

The peak temperature of the loss tangent (tan δ) which characterizes molecular motion in the amorphous part in the PTT fiber is reached at around 110°C, which is 30°C lower than that for PET fiber. It results in good dyeing properties at low temperature. If an appropriate dye is selected, PTT can be stained even at ambient temperature. Complex PTT with natural fiber or regeneration cellulose requires a low temperature dyeing ability. This and the stretch of Solo provide applications in fibers and textiles when complexed with wool, cotton, and Benberg®, etc.

Asahi Kasei and Teijin established a joint company, SOLOTEX Corporation and started production of SOLOTEX®. SOLOTEX® is used for clothing because of its stretch and soft properties and dyeing ability at low temperature, without losing the properties of the combined material. In the materials field, because of its high recovery, it can be used for cars, interiors, and carpets.

2.3.3 Fiber from corn

A biologist at Du Pont developed a new type of bacterium by combining the DNA of two kinds of bacteria. When the bacterium was fed with corn, it produced milky liquid known as 3G, which could react with terephthalic acid to produce 3GT resin. Then the resin is spun to give 3GT Fiber. Du Pont started commercial production of 3G on a scale of 3000 l/day from October 2000 to produce a windbreaker. They intend to construct a 3G plant with the capacity to produce 300 000 l/day. The product is soft, good in elastic recovery, can be dyed at room temperature, and the cost is cheap enough to compete with nylon and polyester. Future usage will be extended from the field of life materials to industrial uses. Each country now gives attention to this new fiber.

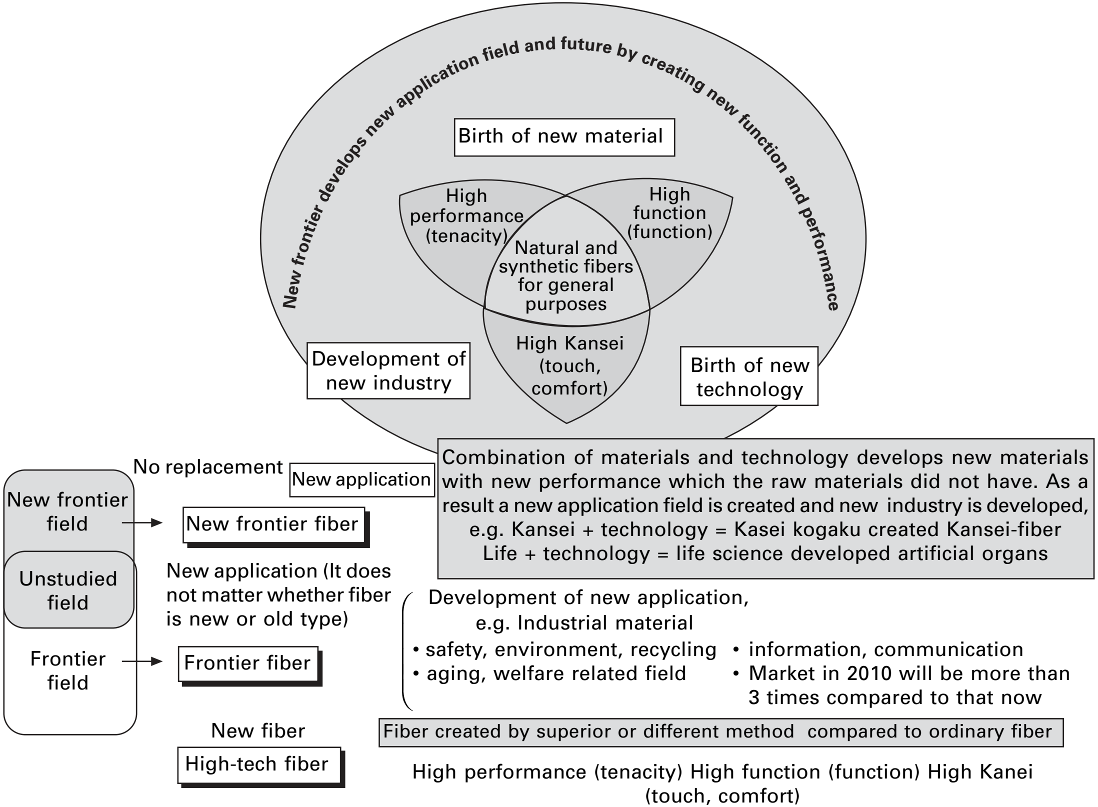
A joint venture company, Du Pont Tate & Lyle Bioproducts, LIC, plans to construct a manufacturing plant to produce 50 000 tonnes of PDO per annum from renewable resources such as corn by the middle of 2005. Accordingly, the production of PTT polymer will increase from 1200 to 60 000 tonnes per annum.

2.4 The distinction between high-tech fiber, frontier fiber, and new frontier fiber

High-tech fiber is made by high technology using advanced science and technology. High-tech fiber is a general term used for fibers made by highly advanced methods or methods which differ significantly from conventional ones. Therefore high-tech fiber is mainly a new fiber. However, *frontier fiber* is based on the development of a new application field, so it is not necessary that it should be a new fiber. To select the fiber and to devise the new application and open up new demand is the criterion which defines *new frontier fiber*, and this is regardless of whether the fiber is old or new. The development of the three fibers is shown in Fig. 2.7.

2.5 Key words for the near future

To develop a new application field, it is necessary to know future needs. High technology, health, comfort, environment, care, optical fiber, sense, special fiber and superfiber are now the key words. Social change and



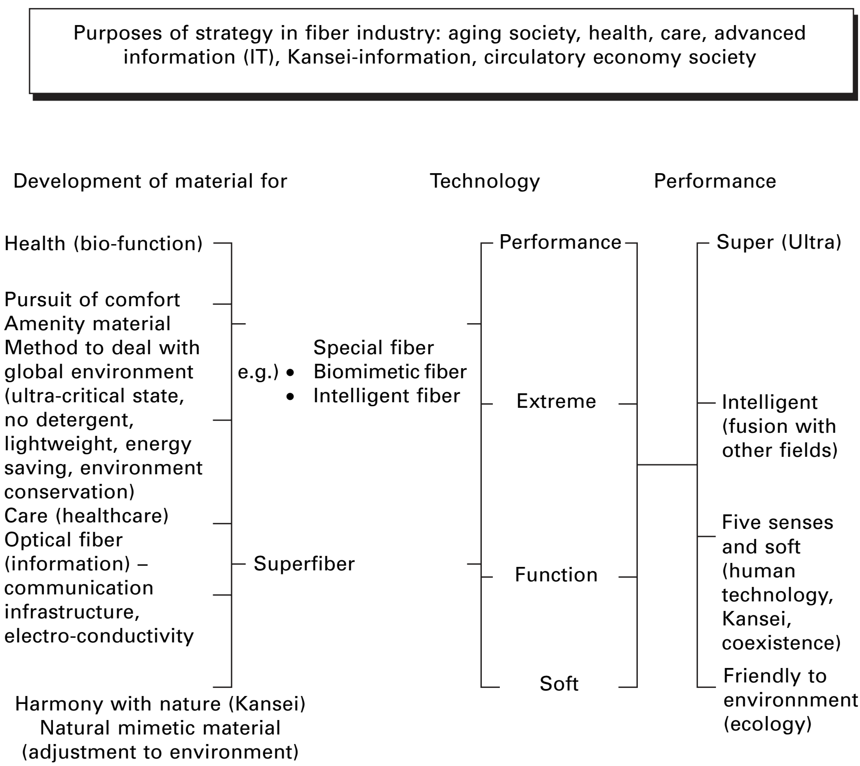
2.7 Concept of general, high-tech, frontier and new frontier fibers.

development leads to the enlargement of the fiber market. Change in society creates a new market. New fiber development in response to the needs of the twenty-first century is shown in Fig. 2.8.

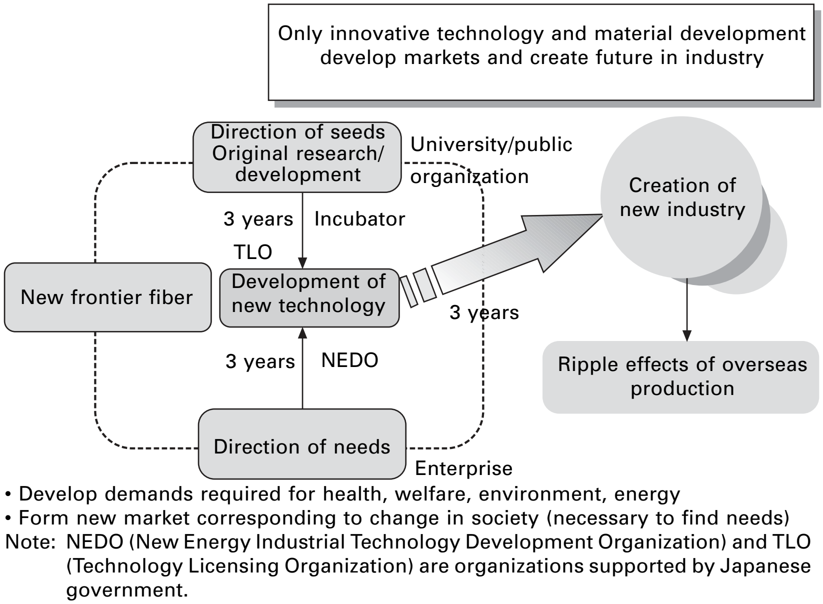
The direction of needs depends on creative technical development. History has taught us that only innovative technology and manufacture can break through into future new markets. The relation between the needs required to activate industry and innovative technology is shown in Fig. 2.9. Innovative technology and products related to development of new markets are included in the idea of 'new frontier'. Fiber as a mature industry cannot be revived as a new frontier without a change in ideas.

2.6 How to develop new application fields

It is essential for new frontier fibers that there is not only a developing fiber market but also new developments in application fields associated with existing industries which have no relation to fiber, and particularly in emerging industries. How fiber can be accepted in these new application fields as a material or as a system technology is important. In other words, to be ahead

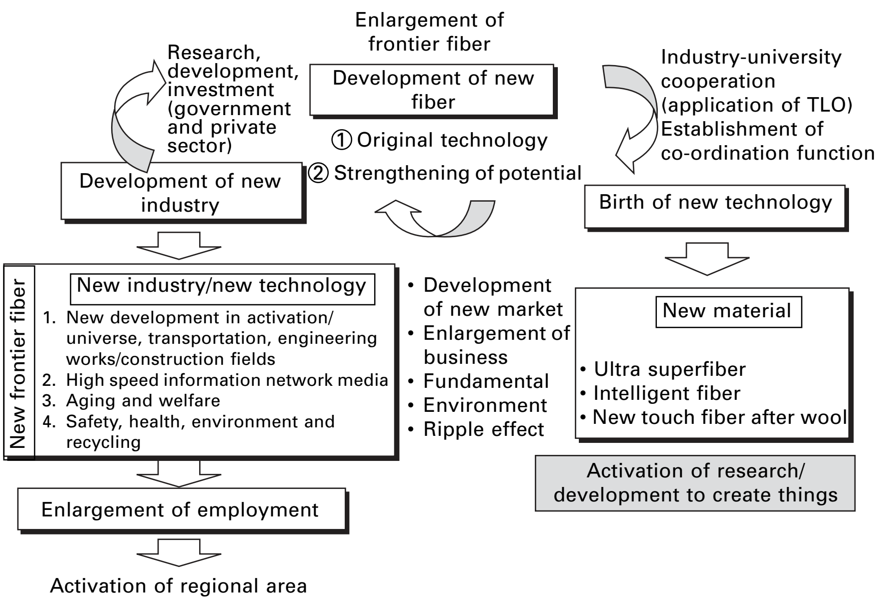


2.8 Development of material in response to the needs of the twenty-first century.



2.9 Relation between needs, seeds and innovative technologies to activate industry.

of others in needs and seed ideas and to develop a new future for industry is the role of a new frontier fiber. An indication of how to develop a new field is shown in Fig. 2.10.



2.10 How to develop a new field.

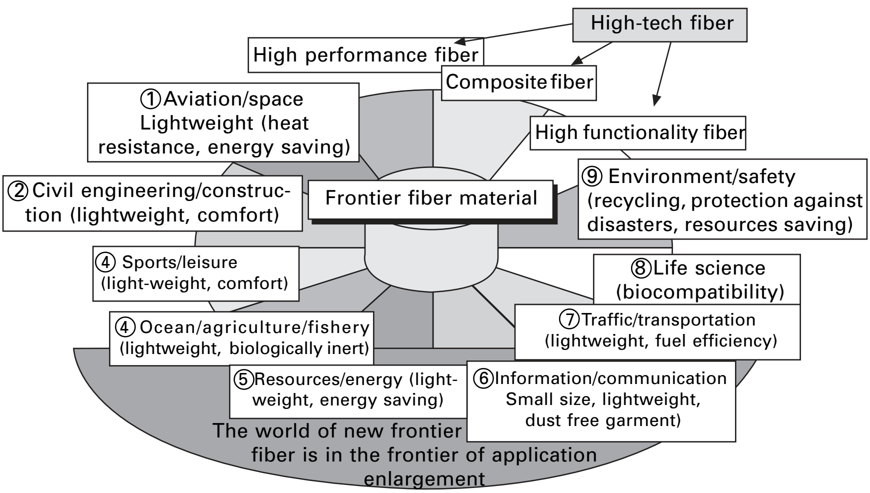
For example, suppose that a deodorant fiber and UV-cut fiber are developed. Each is a high-tech fiber and a frontier fiber when developed. Deodorant socks and apron with flavor are such examples of processing of fiber to add a function. However, this is too naïve a way of thinking. Similar products are already on the market. New frontier fibers require such functions, certainly, but they also need an added dimension to use fiber positively to meet social needs and restrictions.

On current thinking, fiber is a thread that is thin and long. Therefore, basic research and development mainly pursues developments related to the fiber's primary structural nature. New frontier fibers require a connection with different fields of industry, with development and enlargement in both vertical and horizontal directions.

2.7 New frontier field now growing

What types of new frontier are currently growing? Ocean development, space exploration, atomic energy, and clean energy fields are good examples (see Fig. 2.11).

How can fibers be applied in the information/communication field? There are optical fibers made of quartz and plastics. Fiber manufacturers make only plastic optical fiber and Japanese enterprises stand out above the others in plastic optical fiber production. However, plastic optical fiber occupies only minor markets compared to quartz optical fiber. Since plastic optical fiber is suitable for connections over short distances and costs only a quarter of quartz optical fiber, it will have superiority in local area networks used at home and in the car.



2.11 Enlargement of frontier fiber applications.

Fiber technology will also be used in the field of biotechnology and healthcare. How are artificial skin, tendon, and internal organs going to be developed? There is now an artificial organ which works outside the body like the artificial kidney. Embedded type organs need to be developed in the future.

2.7.1 Developments in the medical field

Major fiber manufacturers in Japan are already participating in the medical/care field. In the United States single use disposable materials are used in hospitals, so that waste products have increased many times compared with the past. In Japan linen goods are used, and used repeatedly after washing. Whether or not this system will change to a disposable one remains uncertain.

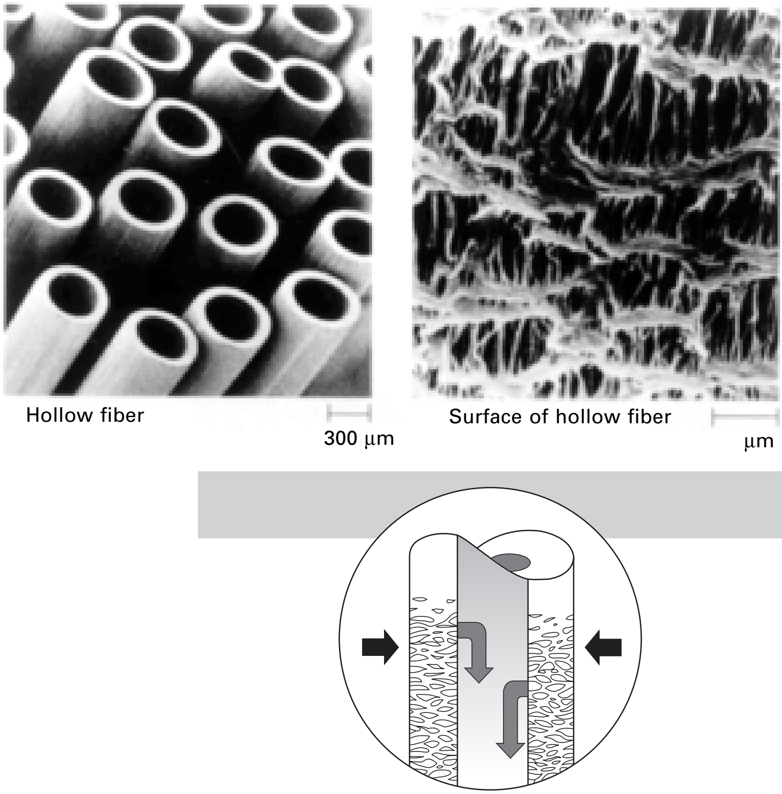
The development of artificial kidneys depends on the development of hollow fiber membrane. Polymer can be spun into hollow fiber membrane as shown in Fig. 2.12.

Artificial kidney (artificial dialysis membrane) and artificial liver

Artificial dialysis membrane is the most advanced fiber in the medical industry. The total number of patients who suffer chronic kidney disease and undergo kidney dialysis in Japan was 167,000 in 1996 and some 170,000 in 1997. The number of patients who undergo kidney dialysis continuously for more than 20 years was 5812 in 1996. Artificial kidney dialysis is accepted as reliable. The purpose of the development of artificial kidney dialysis membrane is to mimic the ability of kidney to completely remove wastes like urea and albumin. The production process for the artificial kidney and dialyser are shown in Fig. 2.13. One of the side effects of long-term dialysis is a shoulder injury caused by β-2-microalbumin accumulating so that the joint cannot move. Big pores are effective in removing waste. However, other necessary components are also removed.

The problem can be solved by making a monomolecular layer fiber, which is controlled by the relation of surface structure to waste blood. There remain problems to be solved in controlling of material and holes on the surface of the hollow fiber. To improve dialysis membrane development, it is necessary to make fiber more identical to the organ itself. At present, heparin is used to prevent clotting of blood. If the patient who undergoes dialysis is a diabetic, the amount of heparin used must be decreased. Therefore, biocompatibility of the material needs to be achieved.

The metabolism of the liver is very complicated which poses problems for the artificial liver. This can be solved by using a double lumen structure with a hollow fiber within a hollow fiber. Blood is run outside and in contact with liver cells and blood, and after purification is run inside the fiber.



2.12 Hollow fiber and its surface structure (Mitsubishi Rayon).

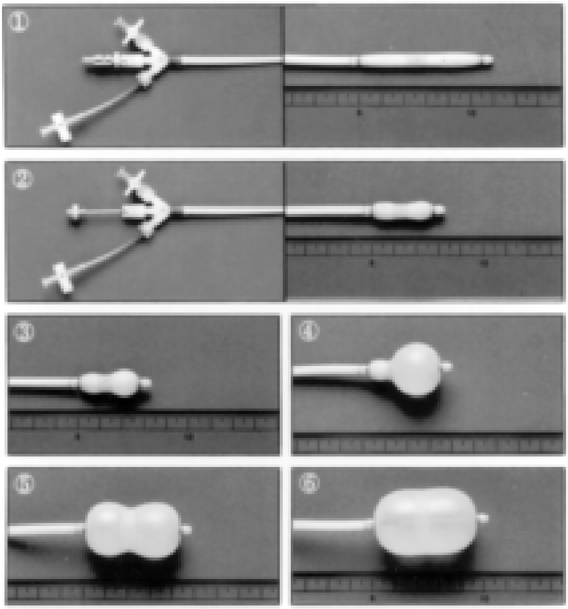
Balloon catheter

A catheter is a tube used for clinical tests and treatment. Catheter treatment was initiated in the United States and subsequently used in Japan. For example, adhesions within blood vessels can be removed by leading a balloon catheter into the vessel; alternatively a balloon catheter with a drug delivery system can be directed to an affected part. The balloon catheter is composed of a guide wire and catheter. The guide wire is used to guide the catheter to the affected part. The catheter manufactured from polyvinylchloride is led into the blood vessel and the balloon, constructed from latex and polyester micromesh, at the distal end is enlarged by a contrast medium introduced by a syringe to open the blocking adhesion and so enlarge the blood vessel.

In mitral valve disease, wire is led into the heart and the blocked part is opened. In pancreas extraction, several blood vessels leading to the pancreas need to be connected quickly. However, if the operation takes time, the blood vessels are connected with tubes coated with heparin to prevent clotting of blood.

2.13 Manufacturing process of artificial kidney and the product (dialyzer) (Toray).

The fine balloon catheter for medical use and balloon catheter developed for the mitral valve operation are shown in Fig 2.14, respectively. The treatment method for the left atrium of the heart using a balloon catheter is shown in Fig. 2.15.



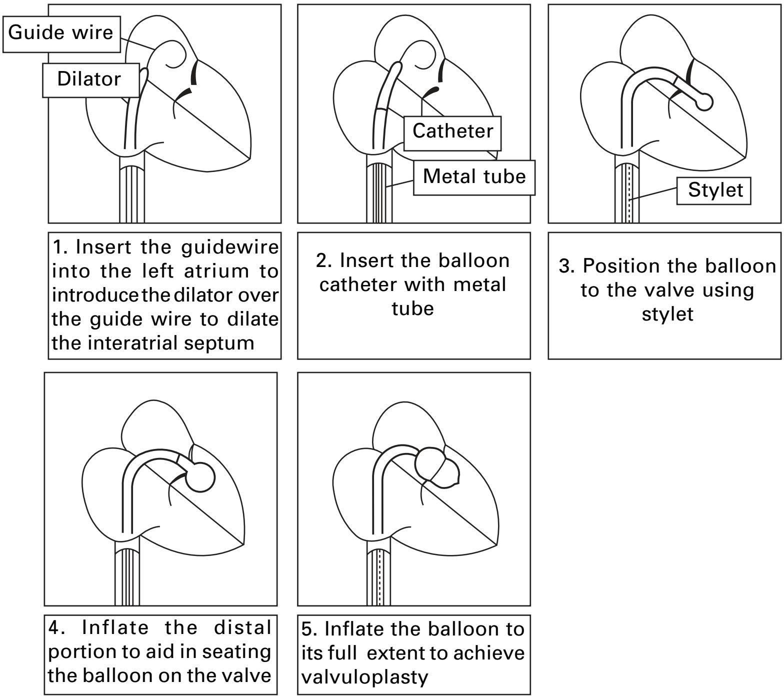
2.14 Balloon catheter developed to treat percutaneous transvenous mitral commissurotomy. Numerical figures show the order of balloon enlargement (Toray).

2.7.2 Enlargement of use for industrial materials

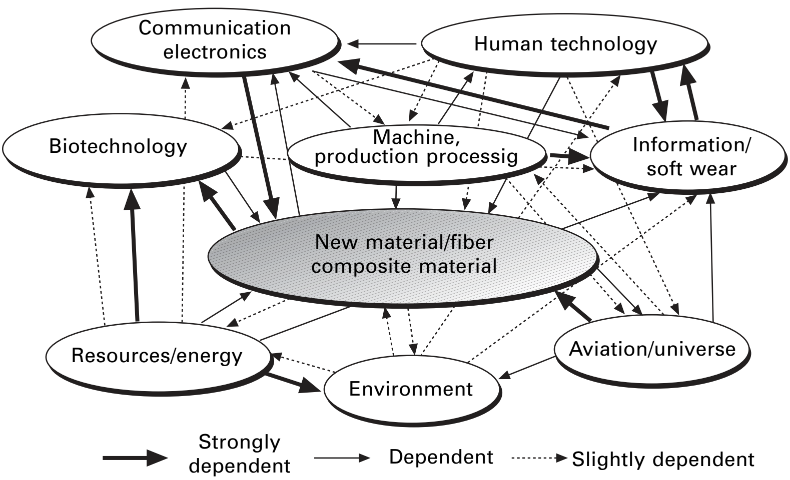
Energy saving, resources saving, lightening, miniaturizing, substitution, and performance improvement are the key words in fiber applications for industrial materials. High performance fiber with superior mechanical properties, complex material made of composite material of high performance fibers with function and base material such as resin, rubber and cement, and composite are the ways to achieve these objectives. Advanced composite material is used in high-tech fields. New application fields can grow by developing advanced fiber composite materials and integrating with other the materials. The relationship between enlargement of fiber application and development is shown in Fig. 2.16.

Life and culture-related fields

Teijin developed a lightweight, easy handling large air membrane, which was given the name *Aeroshelter*®. For outdoor events such as concerts, weddings and exhibitions, there is a need for a large air dome, which can house people comfortably, protect them from sunlight and rain, and which is easy to handle and set up. *Aeroshelter*® is ideal for use over one to seven days, and is easy to handle and store (15 m × 10 m in size). The weight of a conventional tent



2.15 Directions of balloon catheter to treat the left atrium of the heart (Toray).



2.16 Interdependence of fiber application enlargement and development.

dome is 650 g/m^2, but this can be decreased 40 g/m^2 by using Tetoron. The shape of this air dome is completely different from that of a conventional one. It needs only ten minutes to set up and twenty minutes to remove all the air. The total weight is 70 kg for a dome of 15 × 11 m in size, so that two people can transport the dome, which is shown Fig. 2.17. The normal dome can cope with a wind velocity of 5–6 m/sec, and stronger ones with velocities of 12 m/sec. An air beam is used as a structure, made from aramid fiber in a lateral direction and polyester fiber in the longitudinal direction. The inner wall is covered with urethane resin and air fills the inside of the tube. A 25 m × 30 m air dome was used to celebrate the 120th anniversary of Tokyo University and cost about 100 million yen (ca US$ 1 million), which includes the cost of the base construction. Alternatively, *Aeroshelter*® with the size of 15 m × 11 m can reduce the cost to 3 million yen. The Tokyo Dome is of the highest quality. It is made of glass fiber with fluorine finish, and the weight of the membrane is 800 g/m^2, and durable for semi-permanent use. The tension of the dome is 200 kg per 3 cm width. The United States has a long history of using air domes, but the Tokyo dome is the only one recognized as a building in Japan.

Mitsubishi Heavy Industry constructed a cornice capable of being towed to a shipyard in Nagasaki and made out of aramid fiber composite material. Because the cornice is light, one person alone can open and shut the cornice having an area of 3000 m^2.

2.17 Large-sized air dome, easy to handle (Teijin).

Domestic and civil engineering

The Winter Olympics were held in Nagano in 1999 and a windbreak and snowbreak nets were used to enable the jumping to be possible in high winds. Generally high mountain jumping can be performed safely only when the wind velocity is less than 3 m/sec. However, when the jump location is surrounded by mountains, the wind blows consistently at not less than 5–6 m/sec. To allow jumping, therefore, the wind velocity must decrease by a half. Thus the Olympic Committee asked Teijin to develop a material which is resistant to wind velocities of 40 m/sec with a lifetime of more than ten years. Moreover, it must have enough light permeability to prevent a sense of gloom when setup. To do this they developed a new material, KINGLIGHT, which is now used as a windbreak or snowbreak net for roads and highways in Hokkaido. The net used in the Olympic Games is shown in Fig. 2.18. The strength of the material is 300 kg/10 cm, and the porosity is 60%. Producing the material in sheet form is not suitable because of a lack of strength to wind pressure and lack of transparency and light permeability.

Thus nets have now found a variety of practical uses. There is a regulation in Japan that the light from an oncoming car must be banned if the angle of the light is less than 11°. A rough net can shut out light from the opposite carriageway and it is used on highways in Japan.

Snowbreak nets are used in Kushiro city, Hokkaido, to prevent snowdrift on roads. Wind velocity is the slowest at heights of 4–5 times higher that of the net. For example, with nets with a height of 2 m, snow does not drift

2.18 Wind/snow proof net set near jump shanze at Nagano Olympic Games (Teijin).

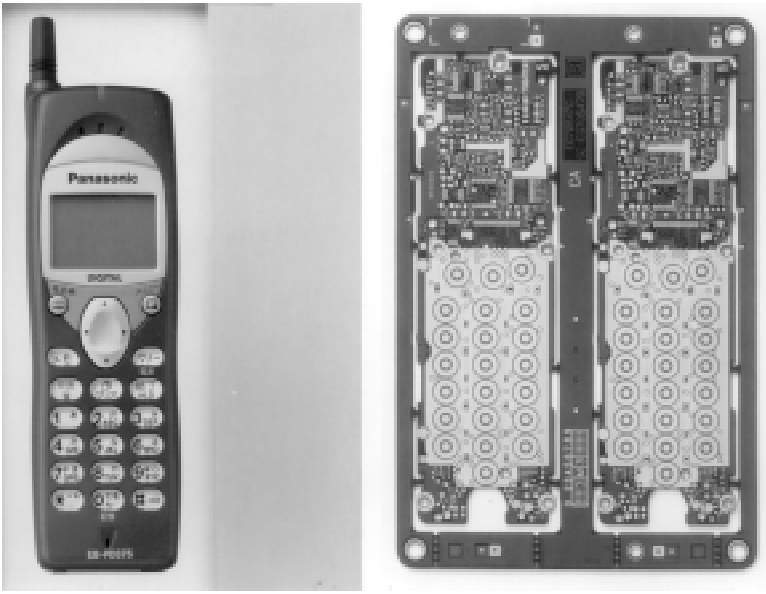
7–8 m from net and starts drifting only at 10 m. Even thin nets are effective in this respect.

Geo-membrane is used for civil engineering works. It is used at the bottom of the waste works to prevent leakage of wastewater. An example is ST LINUS developed by Teijin. The sheet is made of strong polyethylene terephthalate with high elongation. When water leaks, a sensor will detect the leakage and sets in action work to mend the point of damage. This is also used for bank protection as shown in Fig. 2.19. Common polyester fiber elongates only 30–40%, but Teijin developed a polyester which can elongate up to 140%.

Information and communication fields

Fiber materials are used for producing plastic optical fiber and as a subsidiary material for quartz optical fiber. Formerly, composite material of glass fiber and resin was used as a printed base for computers or mobile telephones, but their role has now been taken over by fibers. The use of chopped aramid fiber has decreased the size and price of mobile telephones, which is a market which has increased phenomenally in recent years, and merits the description 'new frontier'. A printed base using Technora for mobile telephones is shown in Fig. 2.20.

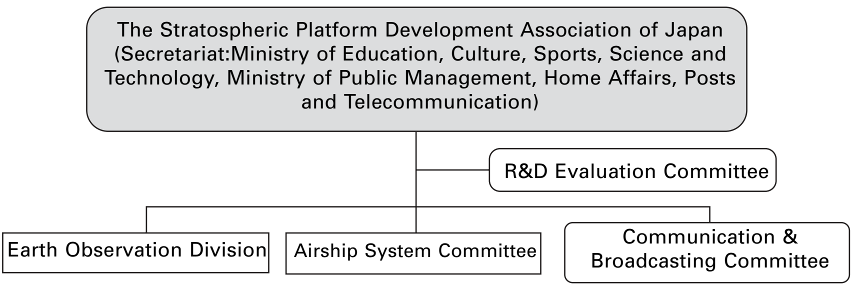
2.19 Construction site using geo-membrane (Teijin).



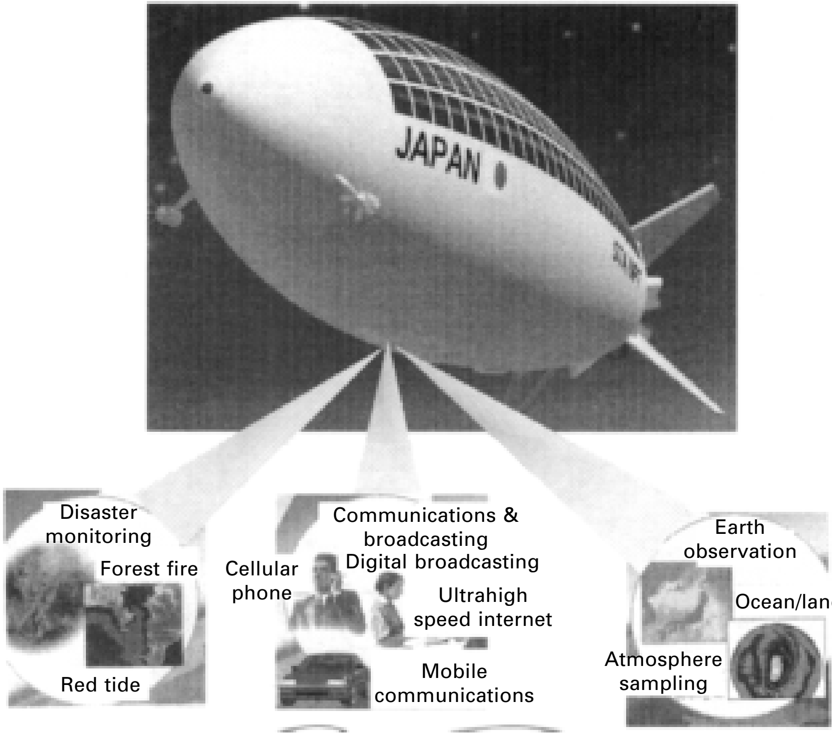
2.20 Printed base for mobile phone using aramid fiber (Teijin).

Development of a stratosphere platform

The Ministry of Education, Culture, Sports, Science and Technology and Ministry of Public Management, Home Affairs, Posts and Telecommunications plan an airship to stay in the stratosphere as a substitute for an artificial satellite. A stratosphere platform was planned, as shown in Fig. 2.21. It will consist of a communication/broadcasting division, an airship division and an earth observation division. The airship division uses fiber as membrane and for this an ultra-strong, yet lightweight material using high-tech fiber is selected. An image of the sky net plan is shown in Fig. 2.22. An airship 200 m in length will stand still in the stratosphere at a height of 20,000 m, and be used to serve ultra high speed internet and digital broadcasting services and



2.21 The stratosphere platform development committee.



2.22 Stratospheric platform.

high function mobile phones. At present satellites go around the earth at the height of 500–1000 km, so that even the radio wave, which can go round the earth seven and half times takes a second to arrive on the ground. Thus the stationary satellite at a height of 20,000 m will contribute to increases in the velocity of internet service.

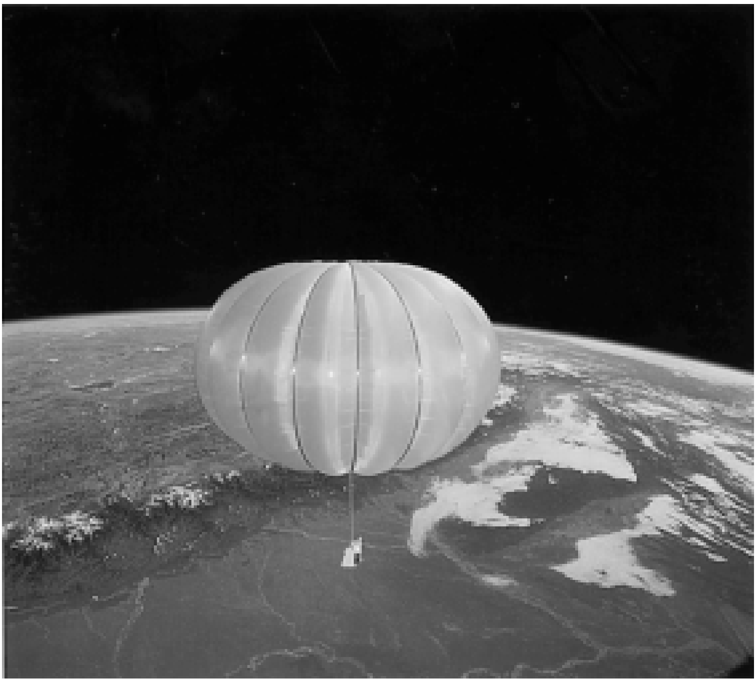
The fiber used should be light, strong, and durable to temperature changes from 100°C to –100°C depending on sunlight. Aramid fiber is suitable for this purpose. The weight of fiber used for the airship will be 17.5 tons. Two hundreds airships are enough to cover all the mobile phones used in Japan. As it will cost 5 billion yen for an airship, the total cost will be 1 trillion yen. The plan at present suggests that an experimental airship could be launched in three years and fully operational airships within five years. At present, the development of the membrane materials is ongoing. The success of the plan will enlarge the new frontier fiber market.

Fabrics with five-layered structure having a gas-barrier property

Teijin and Dimension Polyant (D/P) have developed a fabric suitable for unmanned balloons, such as the Ultra Long Duration Balloon of the National

Aeronautics and Space Administration (NASA). The base material for the balloon is Teijin's lightweight but industrial-strength polyester Tetoron Powerip, laminated with polyester and polyethylene films, creating a five-layered material with UV-resistant, high gas-barrier and low moisture absorption properties. The finest high strength fiber was used to lighten and increase tear strength of the double rip structure. The 140 m diameter balloons will orbit the earth six times in about 100 days from 52 km up in the stratosphere, and will carry about 3.5 tons of instrumentation. During the stay in the stratosphere, the balloon will collect information concerned with atmosphere, space, the sun, and the global environment. The balloon is shown in Fig 2.23.

A trial balloon was launched in October 1999 and first tested in December 2001. The cost required for the project will be 1/100 of achieving the same performance with an artificial satellite. The observation height is lower than that of a satellite so that clearer information can be obtained. Moreover, the balloon is unmanned, so that there is no risk to human life, which is one of its biggest advantages. NASA plans to extend the project for exploring Mars, Venus, and Jupiter.



2.23 Balloon made of five-layered fabric with gas-barrier property (Teijin).

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